Journal of Hydrology 574 (2019) 242–256

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Global agricultural green and blue water consumption under future climate and land use changes

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ARTICLE INFO

This manuscript was handled by Marco Borga, Editor-in-Chief, with the assistance of Yuting Yang, Associate Editor

Keywords:
Integrated assessment model
Crop green water consumption
Crop blue water consumption
Climate change
Land use change

ABSTRACT

Agriculture accounts for 90% of global freshwater consumption and it is expected to intensify in the future. Climate and land use changes are two major factors affecting crop green and blue water consumption, and in this study we explicitly consider the effects of both factors in a consistent modeling framework. Two important research questions are addressed: 1) How will global crop green and blue water consumption evolve over the 21st century under climate and land use changes; and 2) what are the individual and combined effects of climate and land use changes on future crop green and blue water consumption? To tackle these two questions, a crop water use module is developed based on the Global Change Assessment Model (GCAM) and its hydrology module (i.e., Xanthos). Crop specific green and blue water consumption are then calculated at global 0.5° × 0.5° grid scale. Results show that global crop green water consumption increases by 12% in 2090s when compared with that in 1971–2000, and climate change dominates over land use change in determining the trend of global crop green water consumption. However, expansion in global irrigated area dominates the changing trend of global crop blue water consumption which increases 70% by 2090s, especially in regions with significant irrigated land expansion (e.g. northern Africa, central Asia, China, Mexico, the Middle East, Russia, southern Asia, and Argentina). Furthermore, global crop blue water dependence will increase under climate and land use changes, especially in arid regions.

1. Introduction

Anthropogenic activities have altered the global water cycle significantly both directly (e.g. human water consumption for agricultural, industrial and domestic purposes) and indirectly (e.g. converting natural vegetation into cropland) (Boucher et al., 2004; Bondeau et al., 2007; Tang et al., 2007; Rost et al., 2008; Rodell et al., 2009; Wada et al., 2010; Haddeland et al., 2014; Leng et al., 2014; Pokhrel et al., 2015). Agricultural irrigation, which is the largest human water consumer, accounts for about 70% of global human freshwater withdrawal and about 90% of global human freshwater consumption (Rost et al., 2008; Hoekstra and Mekonnen, 2012; Wada and Bierkens, 2014; Huang et al., 2018), and has contributed to increasing evapotranspiration and decreasing river discharges (Rost et al., 2008; Müller Schmied et al., 2014). Given the rapid growth of global population and increasing food demand over the past several decades, crop green and blue water consumption have increased with the expansion of cropland, especially irrigated land (Klein Goldewijk and Ramankutty, 2004; Siebert et al., 2015). Here, crop green water consumption is known as the evapotranspiration from soil moisture replenished by precipitation in cropland, while crop blue water consumption is the evapotranspiration from irrigation, i.e. water abstracted from rivers, lakes and aquifers (Savenije, 2000; Falkenmark and Rockström, 2006; Rockström et al., 2009a). Previous studies have reported that the annual mean global crop green water consumption (about 5000 km^3/year) is about three times of global crop blue water consumption which is about

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https://doi.org/10.1016/j.jhydrol.2019.04.046
Received 1 December 2018; Received in revised form 27 March 2019; Accepted 14 April 2019
Available online 17 April 2019

1000–1700 km^3/year (Shiklomanov, 2000; Rost et al., 2008; Hanasaki et al., 2010; Liu and Yang, 2010; Chaturvedi et al., 2015). The increase of human water consumption is expected to intensify global water scarcity, which is a significant issue in a number of countries (Oki and Kanae, 2006; Vörösmarty et al., 2010; Hayashi et al., 2013; Hejazi et al., 2014; Wada et al., 2016). Thus, assessing future global agricultural green and blue water consumption and their implications on the sustainable use of freshwater and related food security issue are critical, especially in arid and semi-arid regions, e.g. North China, Central Asia, the Middle East and northern Africa.

Agricultural green and blue water consumption at global scale have attracted considerable attention, and various approaches have shed new light upon the estimates of the present and future state of global agricultural water consumption during the past two decades (Shiklomanov, 2000; Döll and Siebert, 2002; Alcamo et al., 2003; Hanasaki et al., 2008a; Rost et al., 2008; Siebert et al., 2010; Leng et al., 2014; Chaturvedi et al., 2015). Initial estimates of crop blue and green water consumption, e.g. Postel (1998); Rockström and Gordon (2001); Shiklomanov and Rodda (2004), were based on diverse irrigation water use statistics, crop productivities and yields, average evapotranspiration rates, and vegetation distribution maps. Later, many global hydrological models (GHMs) have incorporated crop water use modules to assess crop green and blue water consumption (Döll and Siebert, 2002; Tang et al., 2007; Hanasaki et al., 2008b; Rost et al., 2008; Wisser et al., 2008; Siebert and Döll, 2010; Wada et al., 2011; Pokhrel et al., 2012; Jaegermeyr et al., 2015). However, most studies have focused on historical reconstruction of crop blue water consumption, and only a few simulations have addressed the effects of future global change (e.g. climate and land use changes) on both green and blue crop water consumption. For example, some studies have reported that future climate conditions will lead to an increase in global crop blue water consumption (Wada et al., 2013b; Schewe et al., 2014; Elliott et al., 2014), but didn't explore the effects of changes in cropland area induced by future socioeconomic development, especially future irrigated land which is expected to expand to meet future crop demands for food, feed, and fuel. Hanasaki et al. (2013) considered the effects of irrigated area expansion on crop blue water consumption, but the future cropland projections were assumed exogenously based on expert judgement, similar to that in Shen et al. (2008) and Sulser et al. (2010). Thus, projections of crop green and blue water consumption under an internally consistent set of future climate and land use conditions are still lacking in spite of their great significance. Furthermore, the individual and combined effects of future climate and land use changes on crop green and blue water consumption, which are of great significance to guide the sustainable use of freshwater, are still unknown.

This study utilizes the Global Change Assessment Model (GCAM), which simulates the complex interactions among economy, energy, land use, water and climate systems in a consistent economic framework, to assess how future crop-specific cropland (irrigated and rainfed) will change. Through incorporating a crop water use module into the hydrological model in GCAM, namely Xanthos (Li et al., 2017, 2018), crop specific green and blue water consumption under future climate and land use conditions are estimated globally. This allows the trajectories of the land use change and climate change to be consistent under the same socioeconomics and emissions pathway, which is a critical improvement to previous estimates of future crop water consumption, which usually considered the single effects (climate or land use) or ignore their inherent consistency with concurrent socioeconomics and emissions pathway.

In this study, we focus on two important scientific questions: 1) how global crop green and blue water consumption will evolve over the 21st century under future climate and land use conditions; 2) what are the individual and combined effects of climate and land use changes on future crop green and blue water consumption. The remainder of this paper is organized as follows: description of the data and modeling framework are represented in "data and methods" section; findings about future global crop green and blue water consumption and uncertainties in our estimates are represented in the "results" section; a comparison of estimation in this study with previous studies and broader implications of the results are discussed in the "discussion" section, followed by conclusions.

2. Data and methods

2.1. Datasets

Monthly meteorological data on a global 0.5° × 0.5° grid are obtained from the Integrated Project Water and Global Change (WATCH) for the period 1951–2001, including precipitation, surface mean air temperature, maximum air temperature, minimum air temperature, relative humidity, surface wind speed, long wave downwelling radiation, and short wave downwelling radiation (Weedon et al., 2011). The WATCH climate data, which is based on the reanalysis data set ERA-40 and bias corrected, is served as historical climate input in this study. For future simulations, monthly climate datasets during the period 1951–2099, obtained from the Inter-Sectoral Impact Model Inter-comparison Project (ISI-MIP, https://www.isimip.org/), were generated by five general circulation models (GCMs), namely MIROC-ESM-CHEM, NorES1-M, IPSL-CM5A-LR, GFDL-ESM2M and HadGEM2-ES. Due to the biases between GCM outputs and observations (Piani et al., 2010), climate datasets from these five GCMs were all bias-corrected using the WATCH climate data for the overlapping reference climate (Hempel et al., 2013).

The MIRCA2000 dataset, which was generated based on multi census national and subnational statistics (e.g. harvested crop area and cropping season), provides the monthly crop harvested area and crop growing season for all the major rainfed and irrigated crops for the year around 2000 (Portmann et al., 2010). In this study, cropping period lists (CPL) from the MIRCA2000 dataset, which provides the monthly growing area, start and end month of cropping period for 26 irrigated and rainfed crops at a spatial resolution of 0.5° × 0.5° for the years around 2000, are used. We reclassified the 26 crops from the MIRCA2000 into 12 crops categories defined by the GCAM model (details in Supplementary). Thus, monthly growing area and the growing pattern of all 12 irrigated and rainfed crops for the years around 2000 at 0.5° × 0.5° spatial resolution are established.

2.2. Modeling framework

The modeling framework consists of several models that are necessary to simulate future land use and land cover change (LULCC), and how both LULCC and future climate affect crop blue and green water consumption globally over the 21st century (Fig. 1). More specifically, GCAM and two of its ancillary modeling tools (Demeter and Xanthos) are used. GCAM is used to simulate how land use may change over time. Given that GCAM is an integrated human-earth system model where land use decisions are made at regional scale (e.g., water basin scale), Demeter, a disaggregation tool, is then used to map crop information from regional to grid scale. Cropland information is then incorporated into Xanthos, a global hydrologic model, to simulate crop blue and green water consumption under future climate and land use conditions. The following describes each of the three modeling tools in more details.

2.2.1. GCAM

GCAM is an open-source community model with representation of relationships among economy, energy, land use, climate, and water systems (Clarke and Edmonds, 1993; Edmonds et al., 1997; Kim et al., 2006). GCAM is often used to simulate different radiative forcing (representative concentration pathways, RCPs) and socioeconomic scenarios (shared socioeconomic pathways, SSPs) using a consistent accounting framework (Calvin et al., 2014, 2018). GCAM is forced by

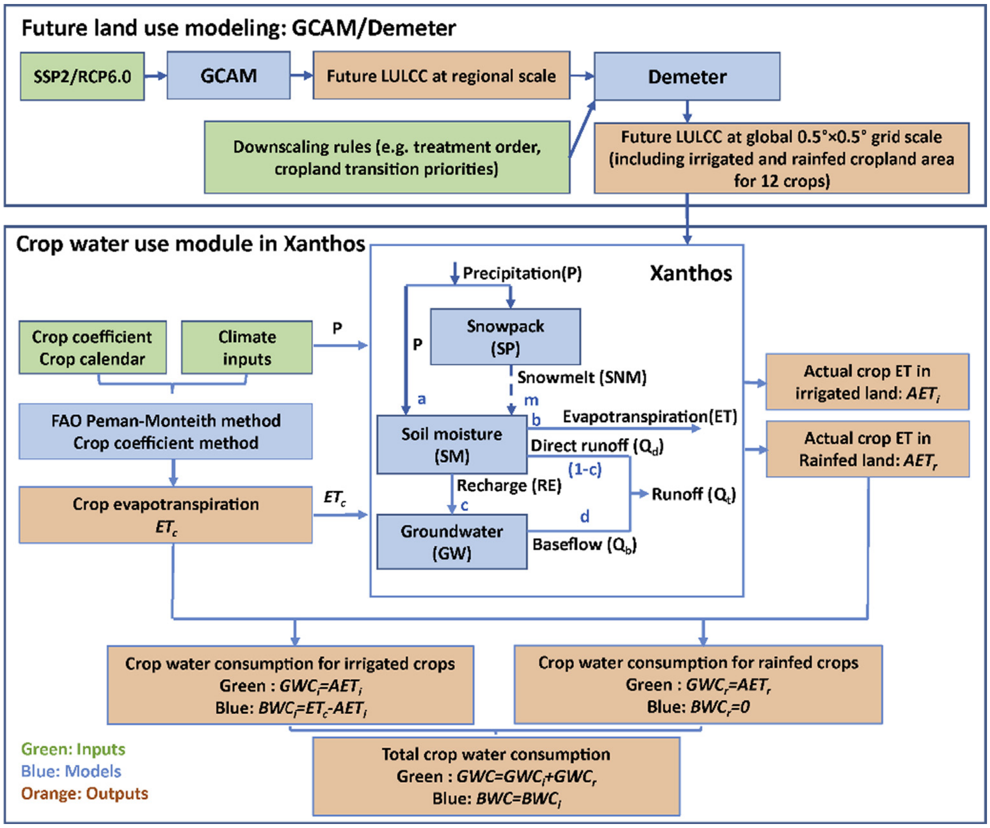

Fig. 1. Schematic representation of model framework for calculation of crop green and blue water consumption.

present and future populations, labor productivities, resource availabilities and energy and agriculture technologies. Regional population and labor productivities assumptions drive the energy and land use system to produce, transfer, and provide energy services as well as to produce agriculture and forest products, further to determine land use and land cover. In this study, the cropland areas for 12 crops (both irrigated and rainfed) are generated by GCAM at the water basin level, i.e., 235 basins globally (Liu et al., 2018), from 2005 to 2100 under the SSP2 and RCP6.0 scenario (see Section 2.3). The 12 GCAM crop categories are corn, fiber crop, fodder grass, fodder herb, miscellaneous crop (misccrop), oil crop, other grain, palm fruit, rice, root tuber, sugar crop and wheat.

2.2.2. Demeter

Demeter is an open-source community LULCC downscaling model, which is designed to generate high-resolution gridded time series representation of LULCC projections from country (or region) level to grid level (West et al., 2014; Le Page et al., 2016; Vernon et al., 2018). The downscaling algorithm is supported by a number of user-defined settings, including the treatment order (i.e. which LULCC type should be downscaled first) and transition priorities (i.e. which type of land swaps are favored, e.g. irrigated rice expansion preferentially into rainfed rice rather than grassland). Demeter uses an intensification and extensification process applied to each LULCC type, and downscales LULCC projections from region (or zone) to the resolution of the base layer (i.e. observed spatial LULCC data, e.g. MIRCA2000). Notably, LULCC types from both projected and observed data are harmonized. In this study, LULCC projections are simulated by GCAM at basin level from 2005 to 2100, including changes in cropland area for 12 crops (both irrigated and rainfed). To assess the uncertainty associated with the parameters in Demeter, five alternative downscaling allocations (i.e. treatment order and transition priorities) are defined, and 5 gridded LULCC datasets are generated. Therefore, future gridded monthly growing area of 12 crops (both irrigated and rainfed) are established based on the gridded downscaled future results from Demeter and historical monthly crop growing area in MIRCA2000 (more details shown in Supplementary).

2.2.3. Xanthos

A crop water use module which estimates crop-specific green and blue water consumption is built upon the hydrologic module in GCAM, i.e. Xanthos (Li et al., 2017; Liu et al., 2018). In this study, the crop water consumption is simulated using the crop coefficient method for each 0.5° × 0.5° grid at a monthly time step (Allen et al., 1998). Monthly crop evapotranspiration, ET_c (mm month^{-1}), which mainly depends on crop development stage and crop types, is estimated as:

$$ET_c = k_c ET_0; \tag{1}$$

where k_c is the crop coefficient, defined according to Allen et al. (1998) and Siebert and Döll (2010), and values for 12 crops are shown in supplementary (Supplementary Table S1); ET_0 is the monthly reference evapotranspiration (mm month^{-1}), calculated by FAO Peman-Monteith method (Allen et al. 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \times n; \tag{2}$$

where Δ is the slope of the saturated vapor pressure versus air temperature curve (kPa °C^{-1}); R_n and G are the net radiation and the soil heat flux, respectively (MJ m^{-2} d^{-1}), which are obtained at monthly scale first (MJ m^{-2} month^{-1}) and then divided by n (the number of days in a month) to get the average daily value; γ is the psychrometric constant (kPa °C^{-1}); u_2 is the wind speed at 2 m height; $e_s$and $e_a$are saturated vapor pressure and actual vapor pressure (kPa), respectively; T is the monthly mean air temperature (°C). Here, e_s, e_a and T are calculated by using the maximum and minimum air temperature averaged over a given month (T_{max} and T_{min}) following instructions in Allen et al.

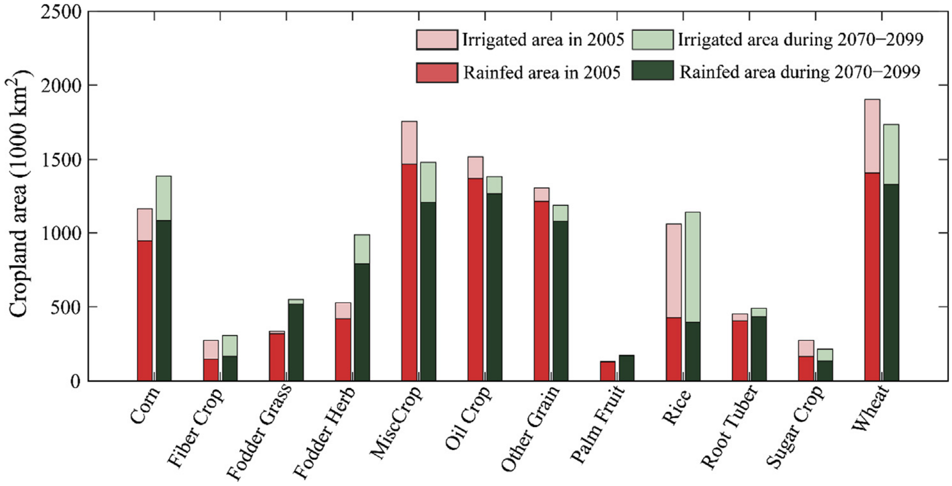

Fig. 2. Global cropland area of 12 major crops for the year around 2005 and the period 2070–2099.

(1998).

For rainfed crops, the crop-specific actual evapotranspiration AET_r during their growing seasons, which is all green water, is calculated by Xanthos, with soil water balance as follows (Liu et al., 2018):

$$AET_r = P + SNM - \Delta S - RE - Q_d; \tag{3}$$

where ΔS is the changes in soil moisture (mm month^{-1}); P is the precipitation (mm month^{-1}); SNM is the snowmelt (mm month^{-1}); RE is the groundwater recharge from soil (mm month^{-1}); Q_d is the directly runoff from soil (mm month^{-1}) (Fig. 1). Crop-specific green water consumption for rainfed crops (GWC_r) is:

$$GWC_r = AET_r \tag{4}$$

For irrigated crops, we assume that there are no water constraints for irrigated crops, and the crop-specific actual evapotranspiration, i.e. sum of green and blue consumption, is equal to the crop evapotranspiration (ET_c). Therefore, crop-specific green water consumption for irrigated crops (GWC_i) is the actual evapotranspiration (AET_i) simulated by Xanthos which is the same as that for AET_r, and blue water consumption (BWC_i) is the difference between ET_c and AET_i, calculated as follows:

$$GWC_i = AET_i; \tag{5}$$

$$BWC_i = ET_c - AET_i \tag{6}$$

In addition, fallow land is treated as bare soil both for irrigated and rainfed areas with a constant k_c of 0.2 (van Beek et al., 2011). Total crop green water consumption (GWC) is the sum of green water consumption in irrigated and rainfed land, while total crop blue water consumption (BWC) is the crop blue water consumption in irrigated land, calculated as:

$$GWC = GWC_i + GWC_r; \tag{7}$$

$$BWC = BWC_i \tag{8}$$

In addition to calculating crop blue and green water consumption, we estimate the blue water index (BWI), which is defined as the ratio of crop blue water consumption to total water consumption, to represent the dependence of crop production on blue water (Johansson et al., 2016). A BWI value of 1 indicates that all crop water consumption comes from blue water (i.e. irrigation), and a BWI value of 0 means that precipitation is sufficient for maximum crop yield or no irrigation is implemented. The BWI helps to identify hotspots where crop demands more water from irrigation than soil moisture as a result of high consumption of agricultural blue water, where socioeconomic and environmental systems may face increasing conflicts over water resources (Johansson et al., 2016).

2.3. RCP6.0-SSP2 scenario

This study targets RCP 6.0 and SSP2 scenarios, which is a suitable combination of the scenario matrix architecture and describes a middle of the road development in climate change mitigation and adaption (O'Neill et al., 2014; van Vuuren et al., 2014; Fricko et al., 2017). This combination depicts a moderate evolution of climate change and socioeconomics in the future, avoiding extreme pathways that are less likely to happen with the ongoing international efforts dedicated to mitigating climate change and seeking sustainable development goals (SDGs) (UN, 2015). The projected global population under the middle of road scenario (i.e. SSP2) grows to around 9.17 billion in the 2050s, peaks around 9.4 billion in the 2070s, and then declines to about 9 billion by the end of this century (Samir and Wolfgang, 2017). Based on GCAM simulation, under the SSP2 scenario, global total cropland area increases by 1.4% from 10.69 million km^2 in 2000 to 10.84 million km^2 in 2100, with most of the increase (5.7%) occurring by 2070, and a subsequent slight decrease of 3.2% between 2070 and 2100 (Figs. S1-2). Generally, global irrigated and rainfed cropland areas increase 11.4% and 4.2% by 2070, respectively. Therein, expansion of rainfed cropland area is mainly for corn (14.4%), fodder herb (62.9%) and root tuber (87.9%), and expansion of irrigated cropland is mainly for corn (40.0%), fodder herb (83.2%) and rice (17.4%), which dominate the changing trend of total global rainfed and irrigated cropland area (Fig. 2). Detail description of changing patterns of future cropland are represented in Supplementary (Figs. S3–5). RCP 6.0 is a stabilization without overshoot scenario in which total radiative forcing level reaches a value of 6 W/m^2 at stabilization after 2100 (van Vuuren et al., 2011). RCP6.0 depicts a global warming of about 4 °C by 2100 with the most rapid increase in temperature in the northern high latitudes areas (Fig. S6). Global mean precipitation increases by about 5.7%, and precipitation increases significantly in the northern high latitudes areas and decreases in the semi-arid areas such as southern Africa, southeastern South America and areas near the Mediterranean Sea (Fig. S6).

2.4. Experimental design

Four experiments are conducted in this study to assess the effects of climate and land use changes on crop blue and green water consumption both individually and in tandem (Table 1). The first experiment, which is forced by the WATCH data for the period 1971–2001 with a 20-year spin up (1951–1970), is used as a benchmark, and also for comparison to previous studies. Cropland area from MIRCA 2000 is used and kept static during the historical period. The second experiment, which is forced by climate inputs from 5 GCMs under RCP6.0 during the period of 1971–2099, is designed to simulate the combined

Table 1
Experimental design.

Experiments	Climate inputs	Land use inputs	Periods	No. of runs	Aims
1. Hist	WATCH	MIRCA2000	1971–2001	1	Model validation
2. Climate_land	5 GCMs (RCP6.0)	1971–2010: MIRCA2000; 2011–2099: 5 land use data from Demeter	1971–2099	25	Combined effects of climate and land use change
3. Climate	5 GCMs (RCP6.0)	MIRCA2000	1971–2099	5	Only climate change effects
4. Land	1971–2010: 5 GCMs (Transient); 2011–2099: monthly average of each GCMs for 1971–2000 (5 GCMs in total)	1971–2010: MIRCA2000; 2011–2099: 5 land use data from Demeter	1971–2099	25	Only land use change effects

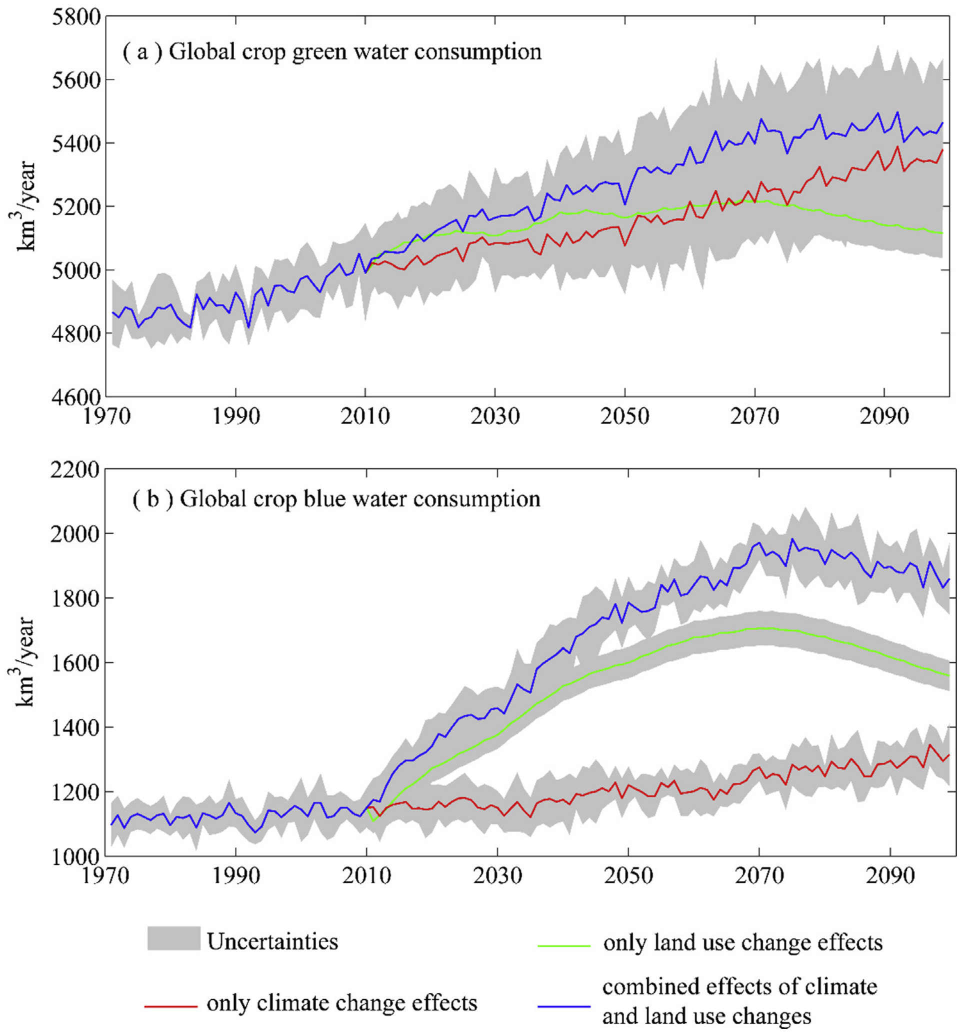

Fig. 3. Time series of global crop water consumption for the period 1971–2099: (a) global crop green water consumption; (b) global crop blue water consumption. The results are the ensemble mean of all the runs in each experiment.

effects of future climate and land use changes on crop water consumption. Therein, land use inputs use the MIRCA2000 data for the period 1971–2010 and land use projections from GCAM for the period 2011–2099. Experiment 3 and 4 are control experiments which are designed to reflect the individual effects of climate and land use changes on crop water consumption, respectively. Different from experiment 2, cropland input in experiment 3 is kept consistent (i.e. MIRCA2000) during 1971–2099. While climate input in experiment 4 during 2011–2099 is based on the monthly average value of each of the GCMs, but with transient land use data for the future period (i.e. GCAM and Demeter estimates, and is the same as that in experiment 2). Experiments 2 and 4 include 25 model runs each (5 GCMs × 5 land use inputs), while experiment 3 includes 5 model runs (5 GCMs × 1 historical land use input). The results focus on the ensemble mean of the multiple simulations in each experiment, and the uncertainty arising from various climate inputs (i.e. GCMs) and land use inputs are also discussed.

2.5. Uncertainty analysis

In this study, the coefficient of variation (*CV*) defined as the standard deviation divided by the ensemble mean value of 25 runs in experiment 2 (i.e. 5 GCMs and 5 LULCC downscaling allocations in Demeter) is used to evaluate the uncertainty from future climate and land use projections. To separate the fractional uncertainty in simulated crop water consumption arising from climate and land use inputs, we use the method of Hawkins and Sutton (2009) and Wada et al. (2013b) who calculated the fractional variance of each uncertainty source by

assuming that each source is independent. The uncertainties in simulated crop green and blue water consumption are separated into two sources: climate inputs (i.e. GCMs) and land use inputs (i.e. LULCC allocations in Demeter), and the total variance (V_t) of crop green and blue water consumption is the sum of the variance from climate inputs (V_c) and land use inputs (V_l):

$$V_t = V_c + V_l \tag{9}$$

Here we use the simulation of gridded crop green and blue water consumption by experiment 2 (25 runs: 5GCMs × 5 land use inputs) to calculate the fractional variance by climate and land use inputs. For V_c, we first calculate the variance at grid level for annual average crop green or blue water during 2071–2099 across the 5 GCMs for a given land use input (i.e. 5 runs: 5GCMs × 1 land use inputs), and by repeating this for each land use input, and the average variance of them is V_c. Similar processes are also adopted for calculation of V_l. Then, the fractional variance of each uncertainty source can be distinguished.

3. Results

3.1. Changes in future crop water consumption

Global crop green water consumption increases about 8.5% by 2099 relative to that of 1971–2000 due to future climate condition. On the other hand, under future land use conditions, global total cropland area continues to increase by 2070, and then slightly decreases between 2070 and 2100, resulting in a moderate increase (6.0%) of global crop green water consumption by 2070s and a mild decrease (-0.8%) during 2071–2099 (Fig. 3a). Generally, global crop green water consumption is projected to increase by 11.3% from ~4886 km^3/year in the historical period (1971–2000) to ~5400 km^3/year by 2070s under both climate and land use change effects, and continues to increase to ~5460 km^3/year by 2090s despite the decline of cropland area, indicating that the effects of climate change on global crop green water consumption is larger than that of land use change. In addition, global crop blue water consumption is projected to increase by 14.1%, 46.6% and 70.3% by the end of this century under the three simulation scenarios, i.e. climate change effects only, land use change effects only, and both climate and land use changes effects, respectively (Fig. 3b). Under climate change effects only scenario, global crop blue water consumption continues to increase slightly in the 21st Century. However, global crop blue water consumption simulated under the combined climate and land use effects scenario shows a similar changing pattern with that under land use change effects only with the peak occurring in 2070s and a slight decline during 2010–2099, indicating that changes in global irrigated cropland dominate the trend of global crop blue water consumption than climate change effects. In fact, even though global total irrigated area increases only 11.4% by 2070, most of the increases occur in arid and semi-arid areas (e.g. Central Asia, North China, and Western US) where crop blue water consumption per unit of irrigated area is higher than some more humid areas with a decline in irrigated cropland (e.g. Southern China, Japan, Central US, and some Europe areas). Therefore, changes in global irrigated area lead to large increase in global total crop blue water consumption, and dominate its changing trend over climate change.

Due to pronounced warming conditions and associated precipitation change (Fig. S6), crop green water consumption during 2071–2099 increases by about 15% when compared with that in 1971–2000 (Fig. S7) with the most pronounced changes in the US, European countries, sub-Sahara regions and eastern China. Climate change also enhances crop blue water consumption globally, especially in the eastern US (by ~30%), northern Brazil (about ~25%), some European countries (by ~40%) and southern China (by ~25%) (Fig. 4a&b). When only considering the effects of changes in cropland area, changes in crop green and blue water consumption shows similar changing pattern with changes in total cropland area and irrigated area, respectively (Fig. 4c&d and Fig. S5). For example, in some developed countries (e.g. Japan, South Korea, UK, Sweden, and Finland), population growth rates are very low, and crop green water consumption decreases as cropland area shrinks; but in some developing countries (e.g. Pakistan, Mexico, Vietnamese, Laos, and countries in Central Asia), crop green water consumption continues to increase as cropland expands to meet the growing demand of crop production due to population and economic growth. Irrigated cropland area also shows increasing trend, e.g. corn in North China; rice in Vietnam, Laos and Pakistan (Fig. S4), which leads to large increase in crop blue water consumption. When considering the combined effects of climate and land use changes (Fig. 4e&f), crop green water consumption increases more than that only under climate change in many regions (e.g. Middle Asia, central China, western US, and eastern Russia) due to expansion of cropland area. Furthermore, land use change aggravates global crop blue water consumption, especially in area with significant irrigated area expansion, e.g. western US, Spain, France, Germany, Central Asia, Middle East and Southeast Asia. Nonetheless, for some regions, the negative effects of land use change exceed the positive effects of climate change on crop green and blue water consumption, further resulting in a decrease in crop water consumption. For example, crop green water consumption decreases in South Sudan, England, Sweden, Finland, northern India and Southeast China, because the decrease in green water consumption as a result of reduction in cropland area outweigh the increase induced by climate change. Similarly, crop blue water consumption decreases in northern India, Southeast China and Japan because the decrease in blue water consumption caused by significant decrease in irrigated area overshadows the increase associated with climate change. In general, as shown in Table 2, climate change dominates the changes in crop green water consumption in most of regions, except for some developing regions (e.g. Africa, Central Asia, Middle East, and Pakistan) where sharp cropland expansions occur to meet the increasing crop production demand and for some regions with significant cropland decrease (e.g. India and Eastern Africa). As for changes in crop blue water consumption, land use change plays a dominant role in regions with significant irrigated land expansion (e.g. Africa, Central Asia, China, Mexico, Middle East, Russia, South Asia, and Argentina), and also in regions with sharp decreases in irrigated land (e.g. Japan, South Korea and Eastern Africa).

In terms of crop types, large green water consumption lies in misccrop (718 km^3/year), oil crop (658 km^3/year), fodder herb (629 km^3/year) and rice (605 km^3/year) during 1971–2000, which also are the dominant global crops in terms of acreage (Table 3). Due to future climate and land use changes, green water consumption is expected to increase for most of crops, e.g. corn (by 30%), fiber crop (30%), fodder herb (49%), where cropland expansion dominates their changing pattern than climate change. As for blue water, rice (247 km^3/year) and wheat (245 km^3/year) are the two major blue water consumer during 1971–2000, but change by 107% and −7% respectively during 2071–2099 as irrigated area increases significantly for rice but decreases for wheat. The increase of irrigated area for rice mainly occurs in Vietnam, Laos, Cambodia, Pakistan and Afghanistan, where rice is the major agricultural product both for food and trade. In addition, global blue water consumption also increases for corn (155%), fiber crop (57%), fodder herb (246%), misc crop (50%) by 2071–2099 relative to that in 1971–2000. Expansion of irrigated area for corn mainly occur in China and US, while irrigated area for fodder herb increases a lot in Eastern US, Spain, Turkey and France (Fig. S4). Due to a significant decrease of irrigated area for sugar occurring in India, Europe and South Asia which surpasses the positive effects of climate change, global blue water consumption for sugar crop also decreases by about 20%.

3.2. Crop blue water dependence

It is evident that BWI in arid regions is larger than that in humid

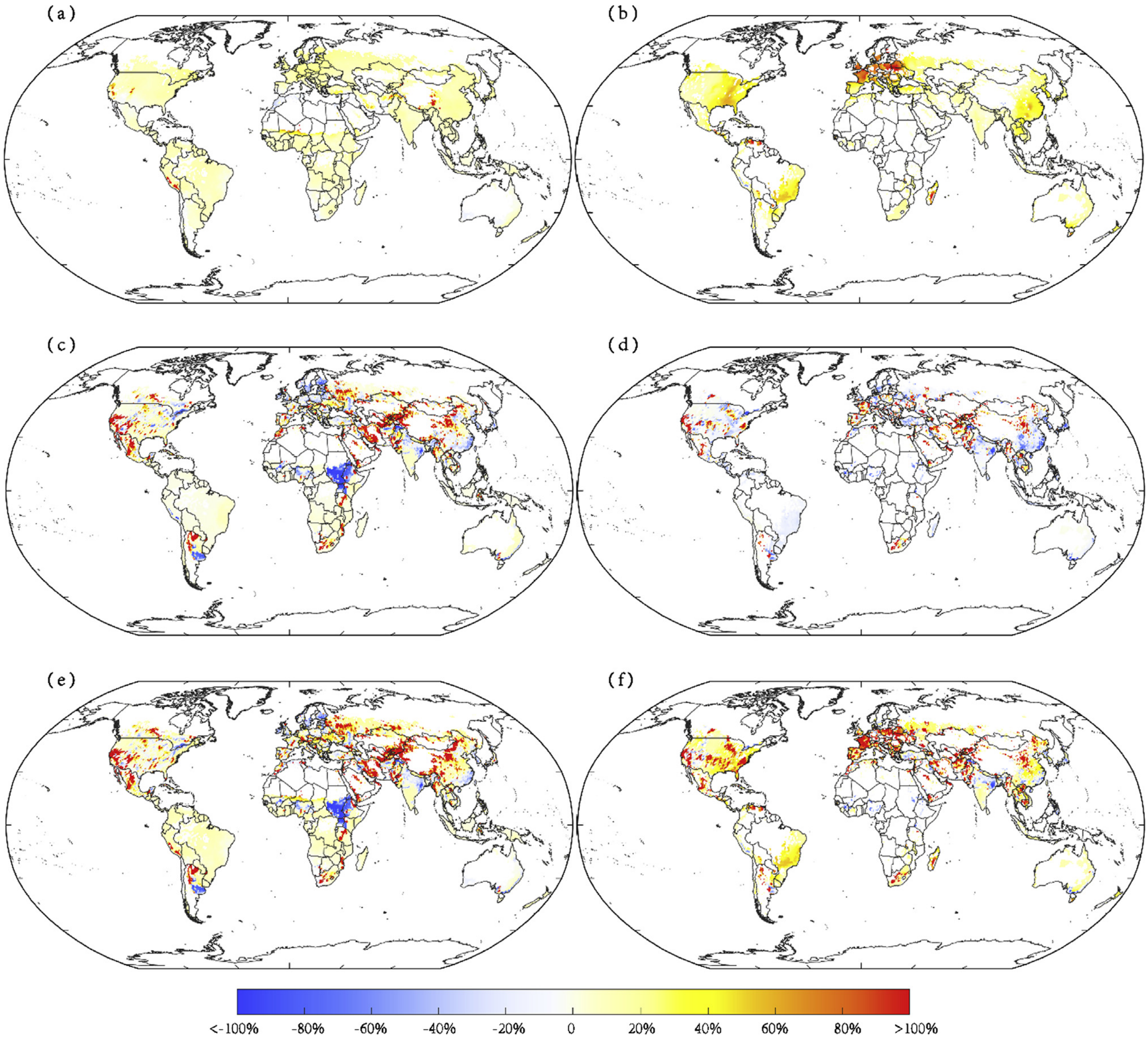

Fig. 4. Percent changes in global crop water consumption during 2071–2099 relative to that during 1971–2000: (a) changes of crop green water consumption only under climate change; (b) changes of crop blue water consumption only under climate change; (c) changes of green water consumption only under land use change; (d) changes of crop blue water consumption only under land use change; (e) changes of crop green water consumption under both climate and land use changes; (f) changes of crop blue water consumption under both climate and land use changes.

areas because of limited precipitation for crop growth in arid regions. For example, crop green water consumption is the dominant water consumption in most regions with BWI $<$ 0.25 like Europe, eastern US, southern China, Southeast Asia, and eastern South America (Fig. S8). Blue water, on the other hand, plays a dominant role for crop production over green water in arid area where irrigated agriculture is the main source of crop production. Globally, global crop BWI increases from 18.6% during 1971–2000 to 26.0% during 2071–2099, and future cropland expansion dominates this increase (Table S2). At the regional level, climate change tends to induce a moderate increase (about 20%) of BWI in most of regions (e.g. eastern US, southern Brazil, and eastern China) because future climate conditions lead to a greater relative increase in crop blue water consumption than in green water, except for India and eastern Africa where the percentage change of crop green water consumption is higher than that of blue water (as shown in Fig. 5a and Table 2). As for the effects of land use change, BWI increases significantly in regions with large irrigated cropland expansion, e.g. China, Middle East, Central Asia, Mexico, and South Africa, and decreases in regions like Australia, Japan and South Korea where irrigated area shrinks in the future (Table 2). Generally, when considering the combined effects of future climate and land use changes (Fig. 5b), BWI increases significantly in western China, US, eastern Africa, Middle East, and some European countries. In addition, as the expansion of cropland area and changing climate conditions, arid regions, e.g. northern Africa, Central Asia, Middle East, and South Africa, where local precipitation can't fully satisfy the demand for optimal growth of crops and irrigation is needed, are expected to move towards higher BWI (i.e. greater fraction of crop blue water consumption), and these regions may face greater competition over water resources.

3.3. Uncertainty analysis

The results presented above are the ensemble mean of global crop green and blue consumption. However, the uncertainties arising from the climate data from GCMs and simulated land use data are still substantial in many regions. As shown in Fig. 6, the uncertainties in

Table 2
The effects of climate and land use changes on future crop green and blue water consumption at regional level: crop green water consumption during 1971–2000 (G_hist, km^3/year); crop green water consumption during 2071–2099 (G_fut, km^3/year); effects of climate change on crop green water consumption (G_climate, %); effects of land use change on crop green water consumption (G_land, %); crop blue water consumption during 1971–2000 (B_hist, km^3/year); crop blue water consumption during 2071–2099 (B_fut, km^3/year); effects of climate change on crop blue water consumption (B_climate, %); effects of land use change on crop blue water consumption (B_land, %).

Regions	Crop green water consumption				Crop blue water consumption			
	G_hist	G_fut	G_climate	G_land	B_hist	B_fut	B_climate	B _land
USA	650.6	724.1	9.1%	5.1%	110.0	160.0	20.9%	18.6%
Africa_Eastern	142.6	90.9	7.7%	−40.0%	15.8	11.7	4.0%	−29.7%
Africa_Northern	33.9	44.7	−15.8%	68.0%	62.1	115.3	13.9%	61.8%
Africa_Southern	75.0	100.6	5.1%	30.8%	2.3	5.8	19.6%	108.4%
Africa_Western	382.9	398.2	9.7%	−4.4%	4.7	8.3	−1.1%	77.6%
Australia_NZ	72.4	70.7	−3.6%	5.2%	13.4	15.5	19.8%	−7.3%
Brazil	313.8	336.3	7.2%	1.8%	4.4	5.6	27.7%	−11.7%
Canada	128.7	139.2	11.8%	−0.9%	1.6	2.1	22.1%	−1.3%
Central America and Caribbean	57.3	61.7	0.1%	13.8%	6.2	7.8	20.0%	−7.5%
Central Asia	56.0	100.9	12.2%	67.9%	67.4	284.9	15.4%	266.3%
China	476.4	559.2	13.9%	6.3%	144.1	244.3	25.1%	34.2%
EU-12	121.7	129.5	16.6%	−6.1%	1.4	2.2	48.9%	−2.8%
EU-15	247.3	262.2	12.0%	−2.0%	31.9	50.8	33.2%	13.6%
Europe_Eastern	134.4	161.9	12.6%	9.3%	3.0	6.4	42.7%	40.5%
Europe_Non_EU	68.3	77.6	9.7%	9.2%	10.4	12.9	25.2%	−4.5%
European Free Trade Association	2.6	3.4	21.9%	6.8%	0.0	0.1	39.6%	370.2%
India	512.4	488.5	7.9%	−5.8%	284.6	286.1	6.9%	−10.3%
Indonesia	225.0	237.9	3.4%	3.2%	2.4	2.8	17.5%	−26.2%
Japan	16.9	17.2	15.2%	−10.1%	1.8	1.6	28.0%	−36.0%
Mexico	65.0	82.2	4.0%	26.4%	24.1	47.0	18.0%	64.9%
Middle East	28.3	49.7	1.6%	90.0%	95.7	295.4	10.7%	181.9%
Pakistan	26.6	30.0	5.6%	20.5%	146.4	188.5	6.2%	20.0%
Russia	276.2	409.5	12.5%	33.4%	10.3	26.8	25.5%	106.8%
South Africa	23.3	31.2	5.5%	31.6%	8.5	29.6	16.7%	199.5%
South America_Northern	16.2	16.5	2.3%	1.2%	0.7	1.2	81.6%	−11.5%
South America_Southern	80.7	86.7	7.4%	1.2%	8.2	9.2	12.3%	−2.2%
South Asia	79.1	83.0	4.1%	5.3%	34.9	53.9	9.2%	36.2%
South Korea	8.3	6.4	15.3%	−30.9%	1.0	1.0	37.7%	−40.6%
Southeast Asia	376.2	406.6	5.1%	4.2%	17.0	20.9	21.1%	−8.2%
Argentina	169.8	212.9	4.4%	23.2%	6.3	11.5	14.5%	50.0%
Colombia	18.8	20.4	8.7%	0.5%	0.1	0.2	33.6%	−17.0%
Global	4886.6	5439.7	8.6%	5.7%	1120.9	1909.0	14.1%	46.6%

estimated future crop green water consumption are rather high (CV > 0.5) in western US, Central Asia and Middle East. The dominant factor driving the uncertainties of simulated crop green water consumption is climate input (i.e. GCMs) in South America, Africa, Australia, and Southeast Asia. On the other hand, land use inputs (i.e. LULCC downscaling allocations in Demeter) dominates the uncertainty in regions like eastern US, Central Asia, Middle East, and West China (Fig. 7). As for crop blue water consumption, large uncertainties (CV > 0.5) mainly occur in Central Asia, Japan, Middle East and some European countries. The dominant factor driving the uncertainty is GCMs in the eastern US, western Africa, southern India, Southeast Asia and some European countries (e.g. Germany and Poland), and is land use inputs in regions like southwest US, Central Asia, Japan and Middle East. In general, in regions with large cropland expansion or reduction,

Table 3
The effects of climate and land use change on global specific crop green and blue water consumption: historical crop green water consumption during 1971–2000 (G_hist, km^3/year); future crop green water consumption during 2071–2099 (G_fut, km^3/year); effects of climate change on crop green water consumption (G_climate, %); effects of land use change on crop green water consumption (G_land, %); historical crop blue water consumption during 1971–2000 (B_hist, km^3/year); future crop blue water consumption during 2071–2099 (B_fut, km^3/year); effects of climate change on crop blue water consumption (B_climate, %); effects of land use change on crop blue water consumption (B_land, %);

Crops	Crop green water consumption				Crop blue water consumption			
	G_hist	G_fut	G_climate	G_land	B_hist	B_fut	B_climate	B_land
Corn	485.9	631.6	9.0%	23.0%	74.4	189.7	21.0%	110.0%
FiberCrop	144.9	188.5	7.7%	26.6%	113.5	178.6	11.9%	37.9%
FodderGrass	13.0	29.5	15.3%	110.6%	0.7	3.8	21.0%	365.4%
FodderHerb	629.3	936.9	10.3%	39.9%	105.1	363.8	17.5%	197.6%
MiscCrop	718.0	665.2	6.5%	−10.6%	139.6	209.0	14.9%	30.1%
OilCrop	658.0	638.4	9.1%	−8.7%	49.4	57.7	19.0%	−5.0%
OtherGrain	436.1	444.1	11.4%	−5.8%	33.8	50.5	12.2%	29.0%
PalmFruit	160.6	206.1	4.0%	24.4%	0.5	2.1	15.7%	226.2%
Rice	605.3	637.9	7.5%	1.8%	247.2	512.0	14.2%	80.1%
RootTuber	244.6	303.3	8.7%	15.8%	14.9	37.1	15.8%	114.8%
SugarCrop	201.9	177.0	5.7%	−13.6%	96.9	77.7	11.1%	−32.5%
Wheat	588.9	581.2	9.4%	−7.0%	244.9	227.0	11.3%	−19.3%

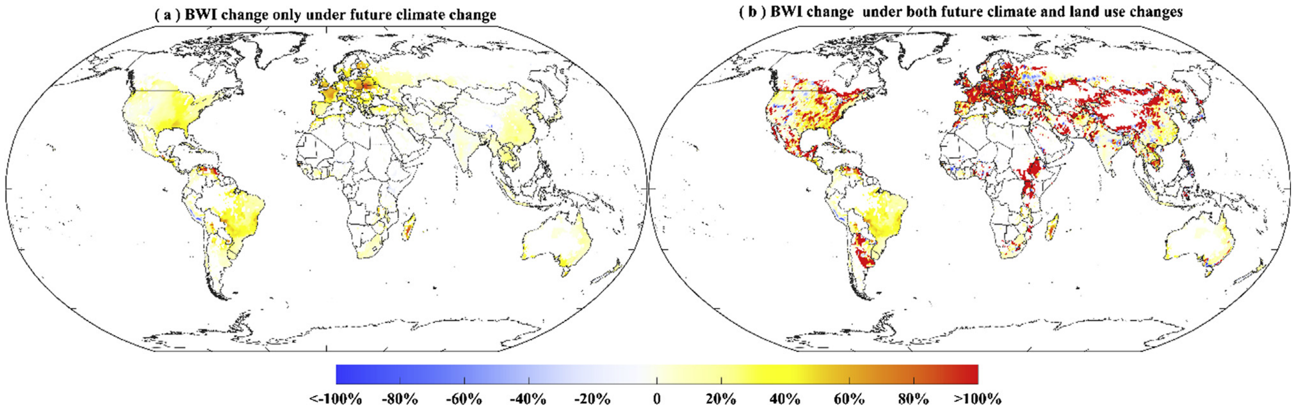

Fig. 5. Percent changes in blue water index (BWI) during 2071–2099 relative to that during 1971–2000: (a) changes of BWI only under climate change; (b) changes of BWI under both climate and land use changes.

Demeter will generate gridded land use data with large uncertainty when using different LULCC downscaling allocations, as a result, land use inputs dominate the uncertainties of estimated crop water consumption. Furthermore, the pre-processes of generating future gridded monthly growing area for 12 crops also lead to large uncertainty in land use data especially in grids without cropland in historical year but with cropland expansion in future. In addition, due to large variability in future climate projection (e.g. precipitation) arising from different GCMs, the uncertainties arising from GCMs can't be neglected in spite of bias-correction.

4. Discussions

4.1. Comparison to previous studies

4.1.1. Comparison to historical estimates at global scale

Estimates of historical global crop green and blue water consumption are compared against previous studies (Table 4). In this study, global crop green and blue water consumption around the year 2000 (average 1997–2001) are estimated as 4954 km^3/year and 1095 km^3/year, respectively. Global crop green water consumption was almost the same as estimates from GEPIC (Liu and Yang, 2010), but about 10–20% less than estimates by other studies (Rost et al., 2008; Hanasaki et al., 2010; Siebert and Döll, 2010; Mekonnen and Hoekstra, 2011; Chaturvedi et al., 2015). Global crop blue water consumption was less than that of H08 (Hanasaki et al., 2010), WBMplus (Wisser et al., 2008), and LPJmL (Rost et al., 2008), and higher than that of GCAM (Chaturvedi et al., 2015), CROPWAT (Mekonnen and Hoekstra, 2011) and GEPIC (Liu and Yang, 2010). Simulated crop water consumption highly depends on not only model framework (e.g. formulation used to calculate reference evapotranspiration), but also cropland extend consideration (e.g. whether fallow land has been included) and climate input (Wisser et al., 2008; Siebert and Döll, 2010).

4.1.2. Comparison to FAO estimates at country scale

At the country level, estimates of annual crop blue water consumption around the year 2000 also show good agreement (with a correlation coefficient of 0.96, Fig. 8) with estimates of irrigation water requirement from the Food and Agriculture Organization of the United Nations (FAO) (http://www.fao.org/nr/water/aquastat/data/query/index.html). However, for countries with large area of paddy rice, e.g. India, China, Indonesia, and Thailand, blue water consumption were over 20% lower than FAO estimation, which might be explained by the reason that FAO model computes irrigation water requirement in paddy rice by adding an additional amount of water (200 mm) for land preparation and flooding for plant protection and the extra water for paddy rice will be mostly returned to rivers or aquifers and is not part of blue water consumption (FAO, 2016). Furthermore, estimates of crop blue water consumption in this study were about 10% higher than FAO estimates in some countries like the US, Spain, and Pakistan, and the disagreement of blue water estimates between this study and FAO might be attributed by the discrepancies in climate inputs, crop growing areas and imprecise crop growing seasons, which have also been reported in previous studies (Wisser et al., 2008; Wada et al., 2013b).

4.1.3. Comparison to ISIMIP historical estimates at grid scale

Spatial patterns of annual mean crop blue water consumption

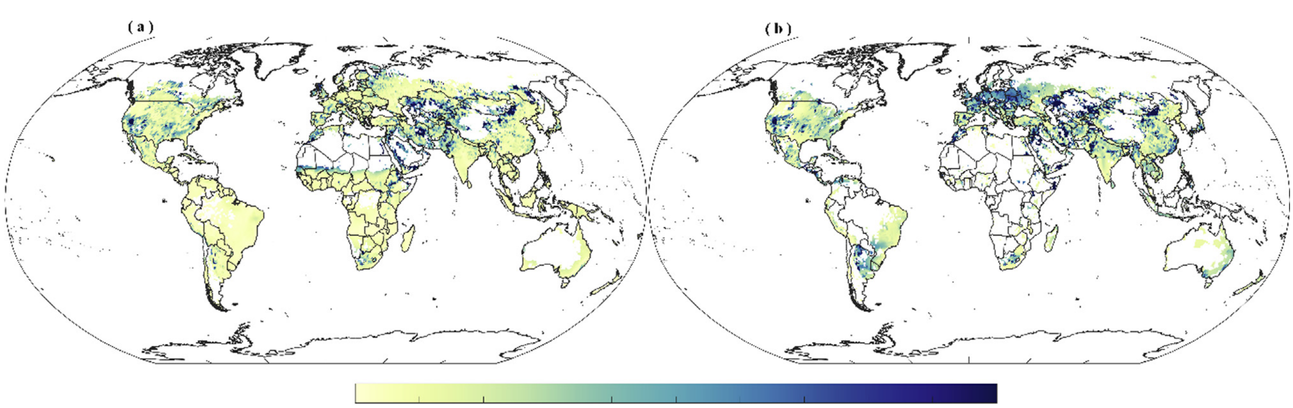

Fig. 6. Coefficient of variation (CV) for global crop green water consumption (a) and crop blue water consumption (b) during 2071–2099. CV was calculated from the ensemble standard deviation and the ensemble mean of 25 projections in experiment 2 (i.e. 5GCMs and 5 land use downscaling allocations).

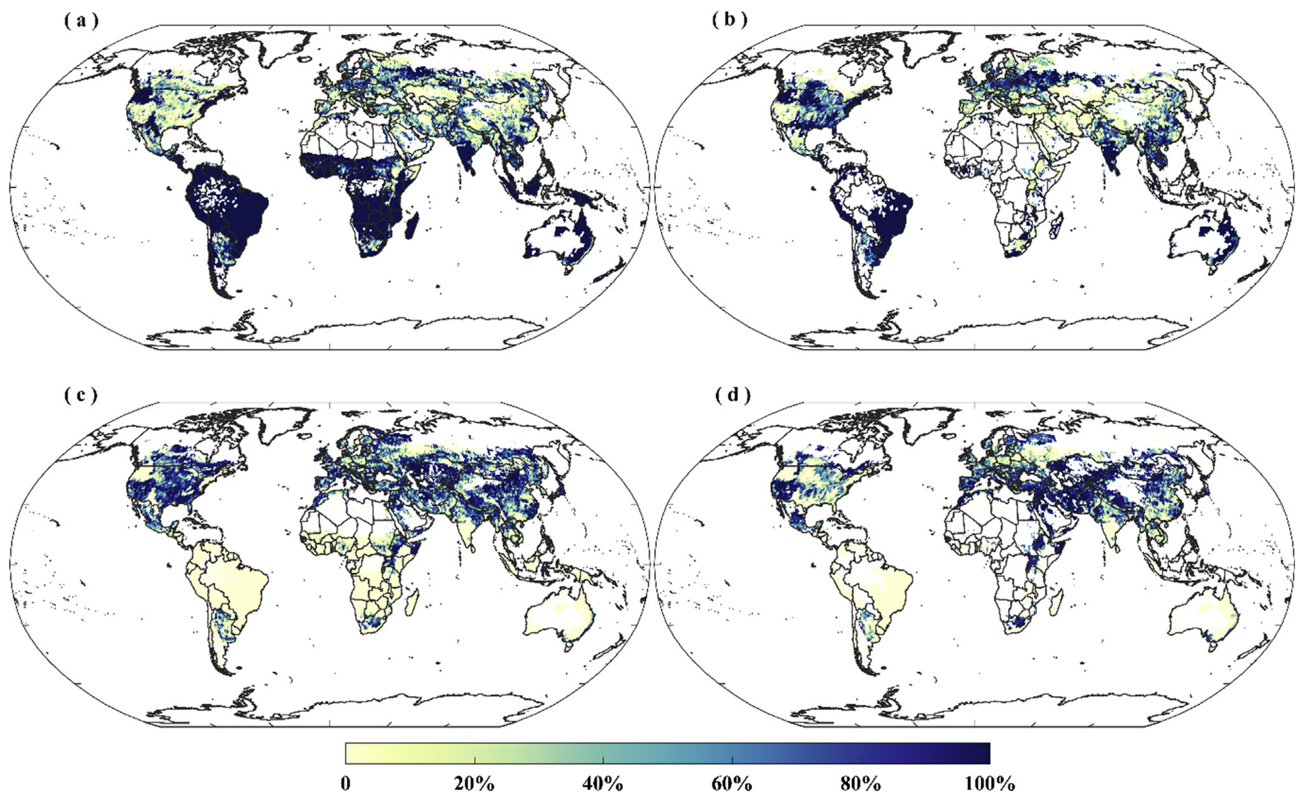

Fig. 7. Fraction of total variance (%) in ensemble crop green and blue water consumption (2071–2099) arising from GCMs and LULCC downscaling allocations: (a) contribution of GCMs to the crop green water consumption variance; (b) contribution of GCMs to the crop blue water consumption variance; (c) contribution of LULCC downscaling allocations to the crop green water consumption variance; (d) contribution of LULCC downscaling allocations to the crop blue water consumption variance.

Table 4
Comparison of simulation of global crop green and blue water consumption with previous simulations: crop blue water consumption (*BWC*, km^3/year); crop green water consumption (*GWC*, km^3/year); crop total water consumption, namely the sum of *GWC* and *BWC* (*TWC*, km^3/year).

Model	BWC	GWC	TWC	Reference	Simulation period
DATA	1500	–	–	FAO (2016)	Around 2010
WaterGap	1300	–	–	Döll (2002)	Avg. 1961–1990
LPJmL	1258	5984	7242	Rost et al. (2008)	Avg. 1971–2000
GCWM	1180	5504	6684	Siebert and Döll (2010)	Avg. 1998–2002
H08	1530	5550	7080	Hanasaki et al. (2010)	Avg. 1985–1999
GEPIC	927	4987	5914	Liu and Yang (2010)	Avg. 1998–2002
WBMplus	1301	–	–	Wisser et al. (2010)	Avg. 1998–2002
CROPWAT	892	5775	6667	Mekonnen and Hoekstra (2011)	Avg. 1996–2005
GCAM	953	5756	6709	Chaturvedi et al. (2015)	2005
This study	1095	4954	6039		Avg. 1997–2001

during 1971–2000 in this study also show a general match with estimates from ISIMIP estimates (Supplementary Fig. S9), which are the ensemble mean of irrigation water consumption generated by 4 GHMs, i.e. WaterGAP (Döll and Siebert, 2002; Alcamo et al., 2003; Müller Schmied et al., 2014), LPJmL (Rost et al., 2008), H08 (Hanasaki et al., 2008a,b), and PCR-GLOBWB (Van Beek et al., 2011; Wada et al., 2011, 2014b). However, crop blue water consumption in this study was over 20% higher than the ensemble mean of ISIMIP estimates in regions with large irrigation water requirement, e.g. western US, India, North China, and Middle East, and were about 20% lower than ISIMIP estimates in some humid areas (Supplementary Fig. S9). Differences in model structures, assumptions and formulations use in GHMs result in different crop water consumption estimates, and uncertainty from GHMs has been proven to be the largest uncertainty source on impacts assessment (Wada et al., 2013b; Piontek et al., 2014). The spatial patterns of crop blue water consumption in this work is within the uncertainties range of ISIMIP estimates (Elliott et al., 2014).

4.1.4. Comparison to previous future projections

The effects of climate change on crop blue water consumption have been estimated in previous studies (Döll, 2002; Wada and Bierkens, 2014; Elliott et al., 2014). In this study, global crop blue water consumption is projected to increase by 14.1% in 2099 when compared with that in 1971–2000 only under climate change effects. This result is in agreement with the estimates of Wada and Bierkens (2014) who reported that global crop blue water consumption is projected to increase by about 14% between 2010 and 2100 under RCP6.0. But the global blue water consumption estimates in this study are lower than those by Elliott et al. (2014) who reported that global crop blue water consumption increase by 25% (with uncertainty range 20%–40%) in 2090s when compared with that in 1980–2010 by 10 GHMs under RCP8.5, and higher than the simulation by Döll (2002) who estimated that climate change would induce about 7% increase in global irrigation water requirement by 2070s when compared with that in 1961–1990. These uncertainties come from different climate projection (i.e. RCPs) and model framework (GHMs). Land use change is also an important factors driving crop water consumption (Fischer et al., 2007). In this study, we show that assuming land use static overtime could lead to underestimating humanity's need for water resources, especially in regions that are likely to expand their cropland productions in the future. As shown in Fig. S1, the amount of land expansion from GCAM is generally lower than previous estimates such as Hanasaki et al. (2013), in which irrigated area was assumed to grow at rate of 0.3%/yr under the SSP2 scenario. In GCAM, irrigation expansion is an economic decision that relies on competing demands for agricultural commodities that are traded in global and regional markets (Calvin et al., 2014).

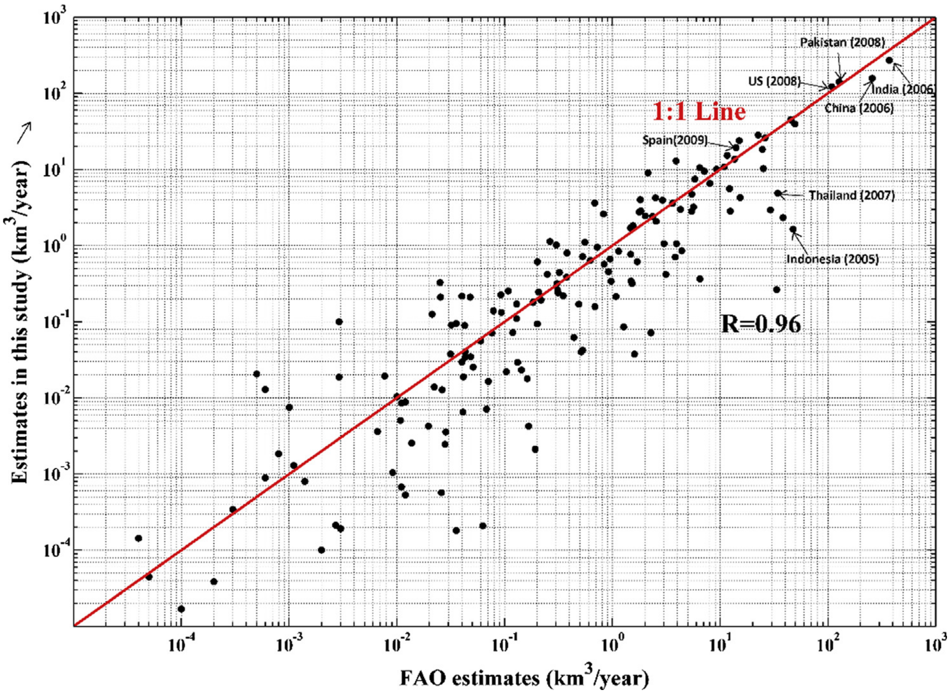

Fig. 8. Comparison of simulated blue water consumption at country level with FAO estimates (FAO, 2016). Here we compare our historical simulation with FAO estimates for a country in a given year. However, our historical simulation only covers 1971–2001. So if the value in FAO estimates is beyond the year 2000, we compare our 2000 results (average 1997–2001) with FAO estimates.

Piontek et al. (2014) have shown that the effects of human activities on water scarcity is comparable to the climate effect in general, and that the human effect dominate in arid and semiarid regions. This is consistent with this work where we show that the land use signal is comparable to the climate signal and tend to dominate in water scarce regions and regions that are projecting large shifts in agriculture productions.

4.2. Limitation and future improvements

The uncertainties of crop water consumption estimates between this study and previous studies come from three parts: model structures, climate forcing and land use inputs. Wada et al. (2013b) reported that the structural uncertainty arising from different GHMs is dominant over that from climate forcing (i.e. GCMs and RCPs). Although this study has relied on a single GHM, the estimation of crop blue water consumption is consistent with the results of the 10 GHMs from ISIMIP simulation (Elliott et al., 2014). Furthermore, this study addresses another important source of uncertainty that is often neglected, which is the LULCC downscaling step. We use Demeter to generate five gridded land use products based on regional GCAM simulation. The uncertainty from LULCC downscaling allocation is comparable to that from GCMs, and LULCC downscaling tend to dominate the uncertainty of crop water consumption than GCMs especially in regions with large cropland expansion or reduction (Fig. 7). Future work should focus on understanding the sources of uncertainty with gridded land use projections to reduce these uncertainties in future simulations of crop water consumption.

Unlike other GHMs which simulate crop growth (i.e. crop calendar) under changing climate conditions (Bondeau et al., 2007; Hanasaki et al., 2008b; Rost et al., 2008; Wisser et al., 2008), we use a prescribed crop calendar compiled by Portmann et al. (2010), in line with that in some models (Siebert and Döll, 2010; Wada et al., 2014b). Notably, the specific crop calendar in a specific region remains static over time. Thus, more dynamic representation of crop information, including crop coefficient, crop categories, crop calendar with future changing environment, would improve the estimation of crop water consumption. In addition, surface resistance was set to a constant value of 70 s m^{-1} when calculating the reference evapotranspiration in Allen et al. (1998), and the increase of surface resistance under an increasing atmospheric CO2 concentration is neglected, leading to over-estimation of future reference evapotranspiration (Yang et al., 2019). It is highly necessary to incorporate the vegetation response to elevated atmospheric CO2 concentration in crop water consumption projections in the future. In addition, Xanthos is run offline with the future climate forcing from GCMs, but not fully coupling into GCMs, where the potential feedbacks were not presented, e.g. the impacts of simulated evaporation by Xanthos on precipitation from GCMs (Schewe et al., 2014). Future works are needed for consistency between the Xanthos simulation and whatever was done in the original climate models.

Crop blue water consumption is assumed to be extracted from nonrenewable water resources when exceeding available water resources at a given grid and month (i.e. no water constraints). Infrastructure development needs is implied to be met in the future land use scenario and this is not necessarily guaranteed. These may lead to over-estimation of irrigation water consumption in arid regions, e.g. Middle East, Central Asia, western US, and northwest China, where regional renewable water supplies can't fully satisfy crop water consumption, as well as in some less developed regions where infrastructure development can't be met in the future land use change scenario. Furthermore, additional evaporation from ponds in paddy rice is ignored, leading to under-estimation of crop blue water consumption for paddy rice. In general, future work needs to take the consideration of water constraints and irrigation water managements for different crop types.

4.3. Broader implications

Freshwater use has been identified as one of the nine planetary boundaries which provides human with a safe operating space in order to prevent unacceptable environmental change (Rockström et al., 2009a,b,c). The freshwater planetary boundary is defined as the maximum blue water consumption in the world beyond the preindustrial situation, and set at 4000–6000 km^3/year (Rockström et al., 2014; Steffen et al., 2015). As the largest consumer of freshwater, agricultural blue water consumption is estimated at about 900–1700 km^3/year at the current stage (Rost et al., 2008; Liu and Yang, 2010; Wisser et al., 2010; Hanasaki et al., 2010; Siebert and Döll, 2010; Mekonnen and

Hoekstra, 2011; Chaturvedi et al., 2015; FAO, 2016), and is projected to increase about 14% in 2100 under climate change effects as shown in this study and Wada and Bierkens (2014). Furthermore, when considering the effects of land use changes, agricultural blue water consumption is projected to increase 70% by 2090s (Fig. 4). Notwithstanding that threshold of freshwater planetary boundary defined by Steffen et al. (2015) isn't yet transgressed, blue water consumption in several regions is already beyond local tolerance limits, and humanity has already experienced the widespread impacts of over consumption of blue water (Gerten et al., 2011; Rockström et al., 2014). Famiglietti et al. (2011) reported that agricultural irrigation resulted in a decrease of groundwater level at a rate of 31 mm/yr in the Central Valley of US, and similar situations were also found in the North China (Tang et al., 2013), India (Rodell et al., 2009) and the Middle East (Taylor et al., 2013). With future climate and land use changes, agricultural blue water consumption in some regions (e.g. West Asia, Middle East and North China) continues to increase to meet the increasing food demand (Fig. 4). Also, meeting environmental water requirements and human's demand for water consumption will be a growing challenge in these water scarce regions which could fundamentally change the environment for human production and socioeconomic development (Rockström et al., 2009b,c).

However, despite the fact that the concept of freshwater planetary boundary strictly focuses on blue water consumption only, green and blue water fluxes are interlinked (Rockström et al., 2014; Jaramillo and Destouni, 2015). The consumptive use of green water in upstream area of a basin typically alters blue water availability in downstream areas. Furthermore, several studies have shown that human induced changes in land and water use (e.g. irrigation) greatly shift the total evapotranspiration, further affect runoff and blue water consumption (Wang and Hejazi, 2011; Destouni et al., 2013; Gordon et al., 2005). As estimated in this studies, global total crop green water consumption is projected to increase by 11.3% from $\sim 4886\,\mathrm{km}^3$/year during 1971–2000 to $\sim 5400\,\mathrm{km}^3$/year in 2070s under both climate and land use change effects. Increasing crop green water consumption would occupy blue water availability for humans which would consequently intensify local water scarcity conditions. For example, many regions have suffered from severe water scarcity, e.g. Middle East, North China, Central Asia and western US where local water availability can't fully satisfy human water demand (Vörösmarty et al., 2010; Wada et al., 2013a; Famiglietti, 2014; Schewe et al., 2014; Mekonnen and Hoekstra, 2016; Veldkamp et al., 2017). Furthermore, there is a rapidly rising trend of crop green and blue water consumption in these hotspot regions as cropland expands driven by growing demands for food and energy, and the BWI increases a lot (Figs. 4 & 5), which would occupy water supply to other sectors (e.g. environment requirement, domestic and industrial) and break the criterion of the freshwater planetary boundary (Gerten et al., 2013).

Thus, the key challenge will be to invest in strategies for sustainable water consumption in relation to the freshwater planetary boundary conception within the integrated green and blue water framework which is an important aspect of the sustainable development goal for water (i.e. SDG6). Furthermore, as global food production may need to rise by 50–70% to satisfy the food demand of an extra 2 billion people by 2050 (McIntyre et al., 2009), resulting in cropland area expansion (Fig. 3), it is important to plan for an integrated climate-land-water framework to meet future food demand for society, as well as reduce pressures on water and land resources (Rockström et al., 2014). One of the most effective measures is to improve water productivity by enhancing soil moisture management and better breeding in crop yield. Since rainfed agriculture accounts for 80% of the world's total agricultural cropland, improving management of green water is very important because upstream management of cropland and green water resources would improve the rainfall partition in a catchment, further benefitting blue water availability to the downstream users (Foley et al., 2011). For irrigated land, besides large scale water supply enhancement through increasing storage of infrastructure and desalination facilities (Wada et al., 2014a), promoting use of waste water and integrating multiple use in irrigation system (e.g. domestic and fisheries) would also increase water productivity (de Fraiture and Wichelns, 2010). Currently, 16% of world population depends on food import to cover their demand for crop products (Fader et al., 2013). Trading agricultural products from highly productive regions with abundant water resources to water limited regions is helpful to reduce regional agriculture water consumption and reduce the risk of exceeding the freshwater planetary boundary. With the growth of global population and associated food demand, a fair and efficient global trade will be needed to sustain local food security and achieve the goal of sustainable development, and trade agreements are expected to reach at global and regional scale which would promote the development of virtual water trade.

In addition, climate change leads to 8.5% and 14% increase in crop green and blue water consumption, respectively (Fig. 6), due to warming in temperature and associated rising evaporation demand (Wada and Bierkens, 2014). Countries' pursuit to achieve their nationally determined contributions (NDCs), mid-century strategies (MCSs), and SDGs will have large implications on the levels of climate impacts and land use changes and their evolutions in the future. Thus, future research should also explore how these forces may affect the coevolution of climate and land systems and how they in turn affect humanity's growing dependence on blue water resources. The challenge lies in identifying potential tradeoffs and synergies across these goals to avoid unintended consequences in term of exacerbating water scarcity conditions (Hejazi et al., 2015).

5. Conclusions

In this study, a crop water use module is incorporated into GCAM system. Crop specific green and blue water consumption are calculated on monthly time step at global $0.5^\circ \times 0.5^\circ$ grid scale with the aid of future climate forcing from GCMs and land use projections from GCAM, wherein the future climate and land use conditions are consistent with concurrent socioeconomic and emissions pathways. This provides a more comprehensive understanding of changes in global crop water consumption than earlier studies, which usually examine this question through the lens of a single factor (i.e. either climate change or land use change), or ignore the inherent consistency between climate, land and socioeconomics. Results show that global crop green water consumption is projected to increase by 11.7% from $\sim 4886\,\mathrm{km}^3$/year in the historical period (1971–2000) to $\sim 5460\,\mathrm{km}^3$/year by 2090s, and the contribution of climate change on global crop green water consumption is larger than that of land use change. Global crop blue water consumption is projected to increase by 70.3% by the end of this century, and expansion in irrigated area is the mainly driver to that. In terms of the spatial patterns, climate change dominates changes in crop green water consumption in most of regions, except in some developing regions (e.g. Africa, Central Asia, Middle East, and Pakistan) where sharp cropland expansion occurs to meet the crop production demand and in some regions with significant cropland shrinkage (e.g. India and Eastern Africa). Changes in irrigated area dominates the changes in crop blue water consumption in most of global regions, especially in regions with significant irrigated land expansion (e.g. Africa, Central Asia, China, Mexico, Middle East, Russia, South Asia, and Argentina). Furthermore, global crop blue water dependence will increase as the climate change and cropland expansion, especially in arid regions. In general, the results in this study improve our understanding of the potential implications future climate and land use conditions on global agricultural green and blue water consumption, which is critical to devise effective adaptation strategies for securing future food and water needs sustainably.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (41730645, 41790424, and 41425002) and the Office of Science of the US Department of Energy through the Multi-Sector Dynamics, Earth and Environmental System Modeling Program. PNNL is operated for DOE by the Battelle Memorial Institute under contract DE-AC05-76RL01830.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.04.046.

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